

Deuterium and Helium Absorption at High Redshift: Mapping the Abundance, Density and Ionization of Primordial Gas

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Spectra of quasars at high redshift with high resolution and high signal-to-noise allow in favorable circumstances detection of absorption by deuterium and ultimately measurement of its primordial abundance. Ultraviolet spectra of high redshift quasars allow measurement of absorption by the most abundant cosmic absorber, singly ionized helium, thereby mapping gas even in the most rarefied cosmic voids. These new techniques already provide significant constraints on cosmological models but will soon become much more precise.

1 Absorption by Primordial Gas

Soon after quasars were discovered in the 1960's it was realized (by Bahcall and Salpeter, Gunn and Peterson, Lynds and others) that their exceptional brightness and simple, smooth intrinsic spectra made their absorption spectra ideal probes of distant material along the line of sight— a unique opportunity to study material at great distances and early times in detail. By 1980 landmark papers by Sargent and collaborators had laid out a considerable detailed statistical knowledge of the absorption, with many important implications for cosmology. The statistical properties of the absorption firmly established that it is caused by cosmologically distributed foreground gas, mostly by clouds constituting an intergalactic or protogalactic population. Some fraction of the clouds with high column density and metal enrichment were identified with galaxies already in the process of chemical evolution. During the 1980's, catalogs of the highest column density “damped” absorbers (especially by Wolfe and collaborators) seemed to isolate a population that could be readily identified as progenitors of modern galaxies.

Theoretical ideas for the absorbing clouds initially explored a very large space of physically plausible populations embedded within the wide variety of extant galaxy formation scenarios. As the Cold Dark Matter paradigm for structure formation sharpened during the 1980's, Rees and others showed that within this picture the absorbing clouds are a natural accompaniment to galaxy formation; they are the condensations of the primordial baryonic material during its early stages of collapse into the dark matter potentials. It became clear that the study of the distribution and the enrichment of the gas through absorption would provide one of the richest and most precise ways of

viewing directly the process of galaxy and structure formation and chemical evolution.

This promise has been realized in the last few years as the pace of progress has advanced quickly both in observations and interpretation. The Keck telescope now provides a qualitatively new type of data: spectra from $z \approx 3$ with high resolution (that is, better than the thermal widths of lines), with signal-to-noise of the order of 100. The Hubble and HUT telescopes provide another qualitatively new type of data: spectra from $z \approx 3$ down to below the He^+ Lyman- α line 304\AA in the rest frame, at lower resolution but still comparable to the earlier work on HI. These two developments now allow (among many other things) the study of absorption not only by hydrogen and metal ions but also by the other important primordial elements in this high redshift gas, deuterium and helium.

At the same time, ideas about the cosmic gas distribution have sharpened quantitatively in recent years, due to hydrodynamic simulations which accurately predict the distribution and motion of matter in hierarchical models of galaxy formation (Cen et al. 1994, Hernquist et al. 1996, Miralda-Escudé et al. 1996, Rauch et al. 1997, Croft et al. 1997, Zhang et al. 1997; see also Bi and Davidsen 1997). Departing from earlier analytic models based on isolated clouds with symmetric geometries such as spheres and slabs, simulations of gravitational collapse from nearly uniform gas (with linear gaussian noise) into nonlinear structures produce dynamical systems with a complex geometry (poetically described as voids, pancakes, filaments, knots) and no sharp distinction between diffuse gas and clouds; similarly, the complex simulated absorption spectra reveal no sharp distinction between lines and continuum. It is now possible to use absorption spectra to apply statistical tests to CDM models which are in some ways cleaner than the traditional ones based on galaxies—since the gas distribution and ionization is computed accurately up to the point where optical depths become large, and do not depend much on uncertainties from star formation and extinction. The cleanest predictions concern the gas in the least dense regions, especially in the voids.

In this context the accessibility of deuterium and helium absorption opens up new types of cosmological tests. The primordial abundance of deuterium is a critical observational test of cosmological theory, both as a test of the basic Big Bang picture and as a measure of the cosmic baryon density, a central parameter of structure-formation models (Peebles 1966, Walker et al. 1991, Smith et al. 1993, Copi et al. 1995, Sarkar 1996, Hogan 1997). Even though deuterium is detected in the Galaxy, high redshift absorption probes its primordial abundance with better control over the effects of chemical evolution, and provides an opportunity to map the abundance in space and its evolution

in time in different environments.

Helium absorption is also interesting for its primordial abundance, but more so for the insights it provides about the density, distribution and ionization of gas at high redshift. Simulated spectra reveal that gas in the most underdense regions, filling the bulk of the spatial volume, is so highly ionized that it produces absorption features with very low HI Lyman- α optical depth. The more abundant absorbing ion He^+ however produces optical depths of the order of unity even in these regions, so its absorption is easily detectable, mapping the distribution of cosmic baryons at the lowest densities.

2 Deuterium Abundance

There are now about eight plausible detections of extragalactic deuterium in the literature, reviewed recently for example in Hogan (1997). There is currently no case where the candidate deuterium feature can be identified positively as such: in every instance, the data could be interpreted as an HI cloud accompanied by another cloud blueshifted by 82 km/sec with a much smaller column density. In the cases where we had thought this was impossible based on the narrow widths of candidate D absorption (Rugers and Hogan 1996ab), new and better data now show that the features are not so narrow after all (Tytler, Burles and Kirkman 1996, and Cowie et al, private communication.) Indeed the new data shows that there must be at least some contamination by HI at the DI Lyman- α feature because the velocity centroid is slightly displaced from the bulk of the hydrogen as measured from the higher Lyman series lines. Thus, the evidence for a high deuterium abundance is not conclusive, but is based on the anecdotal accumulation of several high estimates, some of which are reported in the literature. I describe here briefly some recent work (Rugers and Hogan 1997) to seek a more reliable statistical estimate.

2.1 Interloper statistics from “Pretend” deuterium absorbers

In principle, because of the monotonic destruction of deuterium by chemical evolution, one should pay the most attention to the highest measured abundances. But contamination by hydrogen lines are bound to yield some spurious detections. Indeed, at some level there is always some contamination, since there is some hydrogen absorption at all redshifts— the problem is to quantify its effect on abundance estimates.

To estimate the contamination by hydrogen interlopers, we explore a statistical technique. We have assembled a control sample of “pretend” deuterium candidates associated with hydrogen lines. These candidates are selected the

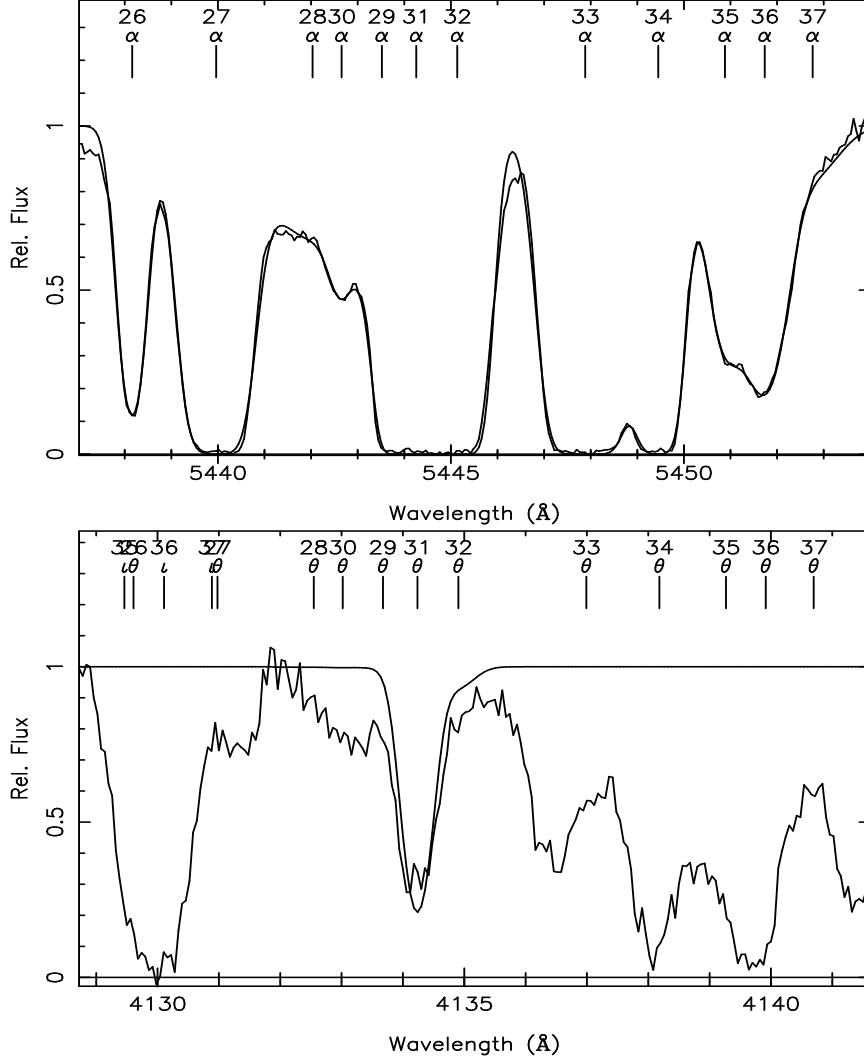


Figure 1: Lyman- α fit (top) for one of seven new deuterium candidates, at $z = 3.478401$ in Q1422+230. The main HI absorption, component 31, has redshift determined by the optically thin Lyman- θ fit (below); the DI feature, component 30, matches this redshift to within the fitting error (difference -3 ± 14 km/sec). Hydrogen contamination (fitted mostly with component 28) is superimposed on the deuterium feature, making the abundance fit very uncertain, $\log(D/H) = -3.53 \pm 0.45$. It can nevertheless be used in a statistical study.

same way the deuterium candidates are selected, in all respects but one: the control sample candidates are drawn from the red side of hydrogen absorbers, rather than the blue side where the real deuterium feature appears. To make a larger sample, the velocity bin to accept a pretend candidate is also larger than that for a deuterium candidate (i.e., $[-60, -100]$ km/sec rather than $[-82 \pm 1\sigma]$ km/sec). The pretend candidates are all interlopers, drawn from a population with the same statistical properties as the deuterium interlopers, including their joint correlations in velocity, column density and width. The properties of two samples can then be compared statistically, using the Doppler parameters and column densities from the line fits.

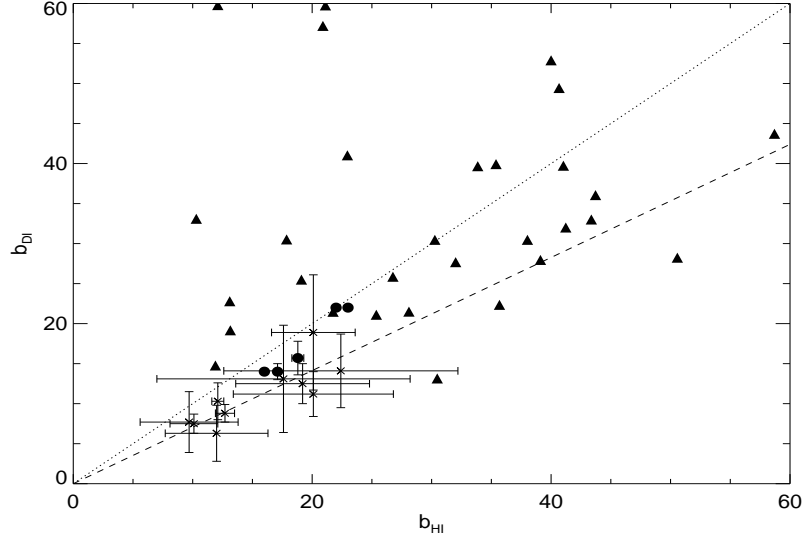


Figure 2: Fitted deuterium and hydrogen Doppler parameters of real deuterium candidates (a uniform sample represented by crosses and published values by filled circles), compared with those in the sample of pretend deuterium candidates, plotted as solid triangles; errors in the latter are omitted to enhance the clarity of the plot. The two lines represent the boundaries of the interval allowed for real deuterium, between the extremes of thermal and turbulent broadening. Unlike the pretend sample, all of the real deuterium candidates are consistent with the allowed ratio. For the new uniform sample, no cut was applied based on Doppler parameter.

For a fair comparison we have also assembled a uniform sample of deuterium absorbers from the same spectra as the pretend deuterium absorbers, based purely on redshift selection relative to HI and metal features. There are

seven new candidates with detectable deuterium features at the right redshift, in addition to the previously published candidates from Rugers and Hogan (1996ab). The reason that they have not been published is that they are not very convincing, or do not yield a precise abundance. One new example is shown in figure 1.

The fitted Doppler parameters (figure 2) show that the claimed deuterium detections are at least mostly real, even if individual cases are suspect. This is true both for the new candidates and for the previously published ones. The D features have statistically narrower profiles than the pretend candidates, consistent with the deuterium identification.

Since we believe the deuterium is statistically real, we can derive a statistical abundance. For the new sample of absorbers, (that is, the uniform sample excluding previously published values), we obtain $\langle \log(D/H) \rangle = -3.75 \pm 0.51$. The reduced χ^2 is 0.70, indicating consistency with a universal abundance. This is certainly not the case for the sample of pretend absorbers; even confining ourselves to those with high HI column (so as to be more directly comparable to the real ones), the abundance of “pretendium” is $\langle \log(P/H) \rangle = -3.2 \pm 2.6$, with a reduced χ^2 of 8.7. Other statistics also display differences. While the real deuterium candidates display consistency with a universal abundance (linear regression coefficient between $N(D)$ and $N(H)$ of 1.00), the pretend sample is a scatter plot (linear regression coefficient between $N(P)$ and $N(H)$ of 0.55.) These statistics are reflected in the scatter plot shown in figure 3. And the distributions of $N(D)$ and $N(P)$ also differ, in the sense that P is not as common as D —another way of saying that for the most part, interlopers may be there but statistically have a lower column density than the real deuterium.

2.2 *Current situation and future prospects*

Although deuterium is detected, its primordial abundance is still uncertain by an order of magnitude. At present, we have a very firm lower limit $D/H \geq 2 \times 10^{-5}$ on primordial deuterium, from Galactic measurements (Linsky et al. 1993, 1996), as well as from some quasar absorbers (e.g. Tytler et al. 1996). There is some evidence for a somewhat higher lower limit ($D/H \geq 4 \times 10^{-5}$) from quasar absorbers (Songaila et al. 1996). A higher abundance than this is not clearly required by the data, although there is some statistical evidence for it and there is no very strong evidence against it, since the low abundances are still found in just a few cases where deuterium may have been destroyed.

Better even than a much larger statistical study would be to find a system where a clear signature of deuterium can be proven, or where the interloper

probability is small. A very promising possibility is a damped absorber in Q2206-199, at $z = 2.559$, with a low metallicity and very narrow lines (Pettini et al. 1994). The interloper problem is much smaller here, both because of the very high column and the low redshift. The low redshift requires HST, but with STIS the entire Lyman series can be seen at once so this is a practical program, currently approved for cycle 7.

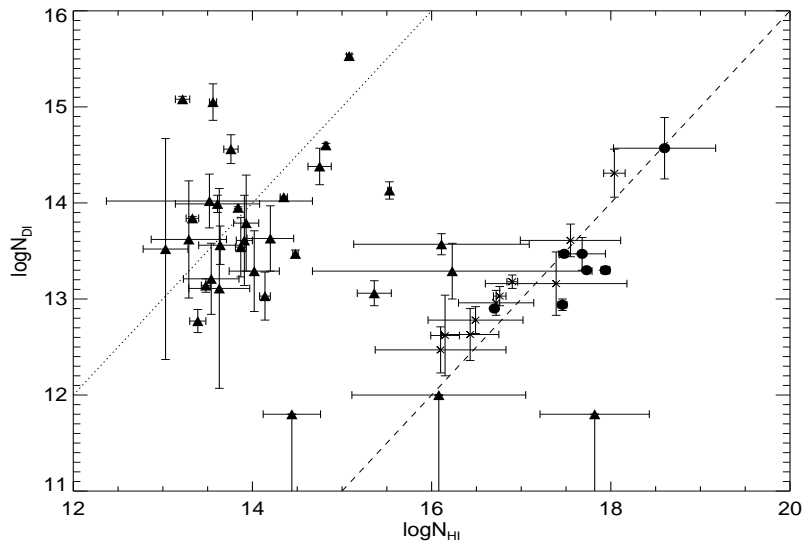


Figure 3: Column densities for fitted hydrogen components and their deuterium counterparts (crosses for the uniform sample, dots for other published values), together with the same quantities for the control sample of pretend candidates (triangles). The distributions are clearly different, as confirmed by statistical tests. Lines correspond to constant D/H .

3 Resolving the Helium Lyman- α Forest: Mapping Intergalactic Gas and Ionizing Radiation at $z \approx 3$

There is certainly HI absorption between the identified lines of the Lyman- α forest. As spectra of higher signal-to-noise ratio are obtained they reveal absorption of progressively lower optical depth. In HI however, even at the highest S/N so far available (about 100 at high resolution), the HI absorption does not yet fill redshift space. Limits on HI continuous optical depth (or “Gunn-Peterson effect”) provide useful constraints on diffuse gas density,

subject to uncertain quantities such as the ionizing radiation field (Giallongo et al. 1992,1994,1996).

Because of its higher ionization potential, the most abundant absorbing ion in the universe is not HI but He^+ . Even in hard radiation fields near quasars it is more abundant by a factor η between 10 and 20. In intergalactic space the ratio is probably greater than 100, so in the emptiest void regions, He^+ produces much more easily detectable optical depths even at modest signal-to-noise. It is therefore the best tool for mapping the distribution of cosmic baryons at the lowest densities. Absorption by He^+ is also the most direct probe of the hard ultraviolet cosmic radiation field, which can be predicted from semiempirical models based on observed quasar and absorber populations (Haardt and Madau 1996). The spectral shape also influences other observables such as the ratio of CIV to SiIV (Songaila & Cowie 1996), so information from helium absorption allows information about relative C and Si abundances to be derived. In situations where the ionizing spectrum is known, such as the near proximity of a quasar, He^+ absorption can be compared to HI absorption to extract independent information about the primordial abundance of helium, an important test of Big Bang Nucleosynthesis.

The difficulty of course is that the Lyman- α transition of He^+ is at 304Å, requiring observations both from space and at high redshift. The first detection of cosmic He^+ absorption was made in Q0302 by Jakobsen et al. (1994) using the Hubble Space Telescope Faint Object Camera (FOC). They found an absorption edge and a large continuous optical depth at low resolution (10Å), $\tau > 1.7$, caused by a mixture of lines and truly diffuse He^+ Lyman- α absorption (Songaila et al. 1995). A similar observation has also been made of the $z = 3.185$ quasar PKS 1935-692, with a similar result (Tytler & Jakobsen 1996).

A significant improvement came from the Hopkins Ultraviolet Telescope (Davidsen et al. 1996), which can reach shorter wavelengths and hence lower redshift than HST, and also provides better resolution and wavelength calibration than FOC. Davidsen et al. observed the $z = 2.72$ quasar HS 1700+64 and found an He^+ edge close enough to the predicted redshift to rule out the possibility of foreground HI as an important contaminant. They also found that the flux below the edge is not consistent with zero, and measured accurately a mean optical depth, $\tau = 1.00 \pm 0.07$. The smaller absorption at lower redshift reflects the increasing ionization of He^+ with time, the thinning due to the expansion, and the conversion of diffuse gas into clouds.

New observations of Q0302 (Hogan et al. 1997) were made to improve both the wavelength calibration and resolution of the He^+ absorption, with enough sensitivity to correlate usefully with the HI absorption (see figure 4).

We can now explore in detail the relative contributions of clouds and diffuse gas, as well as measuring independently the ionizing radiation field and the helium abundance. We find significant He^+ absorption from HI clouds (with optical depth of the order of unity) but also comparable He^+ absorption even in redshift intervals where the best Keck spectrum reveals no detectable HI; thus we directly measure absorption attributable separately to both the clouds and the diffuse gas. Our spectrum suggests nonzero flux at all wavelengths, which constrains the ionizing background spectrum and leads to an upper limit on the density of diffuse gas. Absorption from gas near the quasar, where the incident spectrum is known approximately from the direct measurement of the quasar spectrum, allows independent constraints on the density and helium abundance of the gas.

The main new conclusions from the current data are: 1. The He^+ Lyman- α forest is detected, and indeed discrete clouds identified in HI are responsible for the main He^+ absorption edge in the spectrum; 2. The “diffuse” (redshift-space-filling) medium is also detected, and must have a low density ($\Omega \leq 0.01(h/0.7)^{-3/2}$) consistent with standard primordial nucleosynthesis and models of early gas collapse into protogalaxies; 3. The intergalactic ionizing spectrum is soft ($\eta \geq 100$), although the intergalactic helium is probably mostly doubly ionized by $z = 3.3$; 4. The helium abundance is within a factor of a few of standard Big Bang predictions, over a large volume of space at high redshift. We expect that these conclusions will be made more general and precise with the new 2-dimensional spectroscopic capability of HST/STIS.

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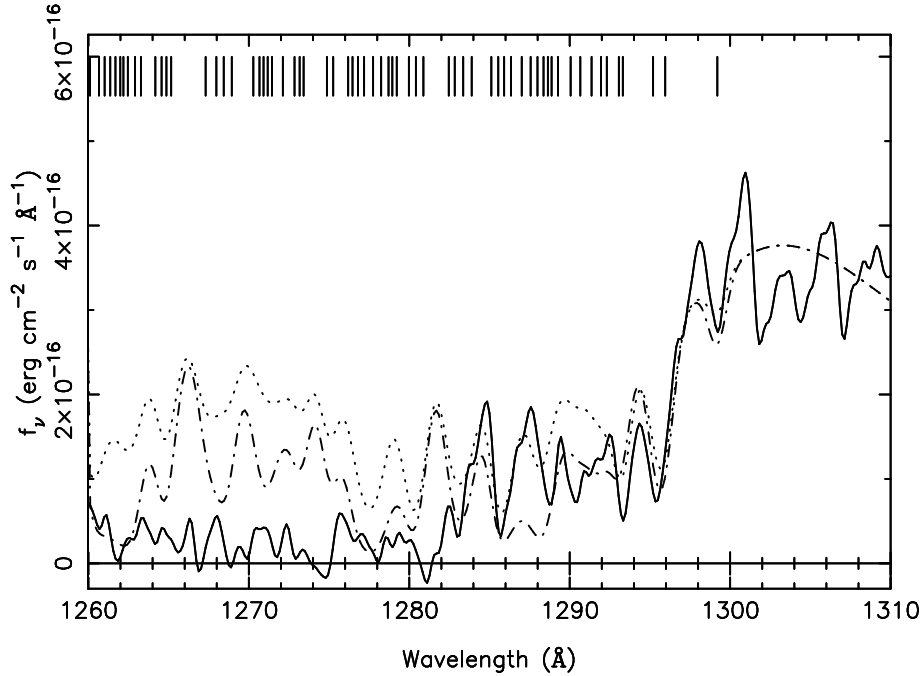


Figure 4: Detail of HST spectrum of 0302-003 near the He^+ edge. The HST spectrum is overlaid with a model spectrum predicted on the basis of the model distribution of HI derived from a Keck spectrum of the HI Lyman- α forest. Ticks indicate the fitted HI velocity components from the Keck spectrum. Doppler parameters and column densities from the fit were used to predict the He^+ absorption spectrum at the GHRS resolution. Two predictions are shown: dotted and dot-dash curves corresponding to He^+/HI ratios $\eta = 20$ and 100 respectively, both models assuming pure turbulent broadening, $b_{\text{He}^+} = b_{\text{HI}}$. The HST and Keck spectra appear to show corresponding absorption features, including the main He^+ edge. Near the quasar, a hard spectrum with $\eta = 20$ is probably sufficient to explain the absorption features entirely with clouds. A large z -filling optical depth is only allowed outside the proximity of the quasar, presumably because the diffuse gas nearer the quasar is doubly ionized. There is significant He^+ opacity ($\tau_{\text{GPR}} > 1.3$) even at the redshift of the conspicuous HI Lyman- α forest void near 1266Å, indicating the presence of diffuse gas between identified HI absorbers. At the same time there is significant nonzero flux everywhere, setting a limit on the density of diffuse, z -filling gas.

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